FROST RESISTANCE OF HIGH STRENGTH CONCRETE

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ABSTRACT

At the Technical Research Centre of Finland (VTT) the frost resistance and salt-frost resistance of 80 MPa concrete have been studied in order to elucidate the reasons for high variations in durability of non-airentrained concrete. These variations have been observed in earlier tests. The project was financed by the Technology Development Fund of Finland (TEKES), Finnsementti Ltd. and VTT.

Keywords: concrete, high strength, frost resistance, salt-frost resistance, durability

1 BACKGROUND

The use of high strength concrete has been studied widely during the last decade. High strength seems, however, not to be the main reason for the use of 80 - 100 MPa concrete. This is evident from the terms used to describe the concrete in various languages: "Högpresterande betong" in Swedish, "High performance concrete" in English, "Hochleistungsbeton" in German and "Béton à hautes performances" in French. These terms do not point to the strength but to overall superior properties. The focus in the use of high strength concrete is moving away from high rise buildings and slender constructions towards bridges, coastal constructions and other constructions where good durability and impermeability are required.

The aim of this study was to elucidate the differencies between 80 MPa concretes made especially with various binders and water-binders ratios.

2 CONCRETE MIXES

In this study 19 concretes were studied. The results of test performed earlier at VTT on nine concretes are used additionally for comparison. The mix proportions of the test concretes are described in Table 1. The cements were manufactured by Lohja Oy (marked with *) or Partek Oy. All cements were Portland cements with the characteristic strength of 40 MPa at the age given after "/". SR means sulphate resistance. The Blaine finenesses were around 580, 470 and 350 m^2/kg for P40/3, P40/7 and P40/28SR, respectively. The water-binder ratio is calculated with an efficiency factor of 0.30 for fly ash. In concrete 10, ground quartz filler 0 - 0.2 mm was used for 3.9% of the aggregate. The same quartz filler accounted for 7.9% of the aggregate in concretes 11, 15, 18, 19 and 22.

In concrete 12, 70% of the granulated blast furnace slag was ground to a fineness of 400 m^2/kg and 30% to a fineness of 700 m^2/kg. In concrete 21 the corresponding percentages were 60% of fineness 400 m^2/kg and 40% of fineness 1000 m^2/kg. Slag was supplied from Rautaruukki works.

The workability measured of the concrete mixes are also listed in Table 1.

The compressive strength of the concretes was tested on 100 mm cubes. The flexural strength was tested on 100 x 100 x 500 mm beams according to Finnish standard SFS 5444. Compressive strength results are shown in Fig. 1. Results from heat treated specimens (stored at 40°C RH 95%, after 7 days normal curing at 20°C RH 95%) are marked with an asterisk. Other specimens were cured normally.

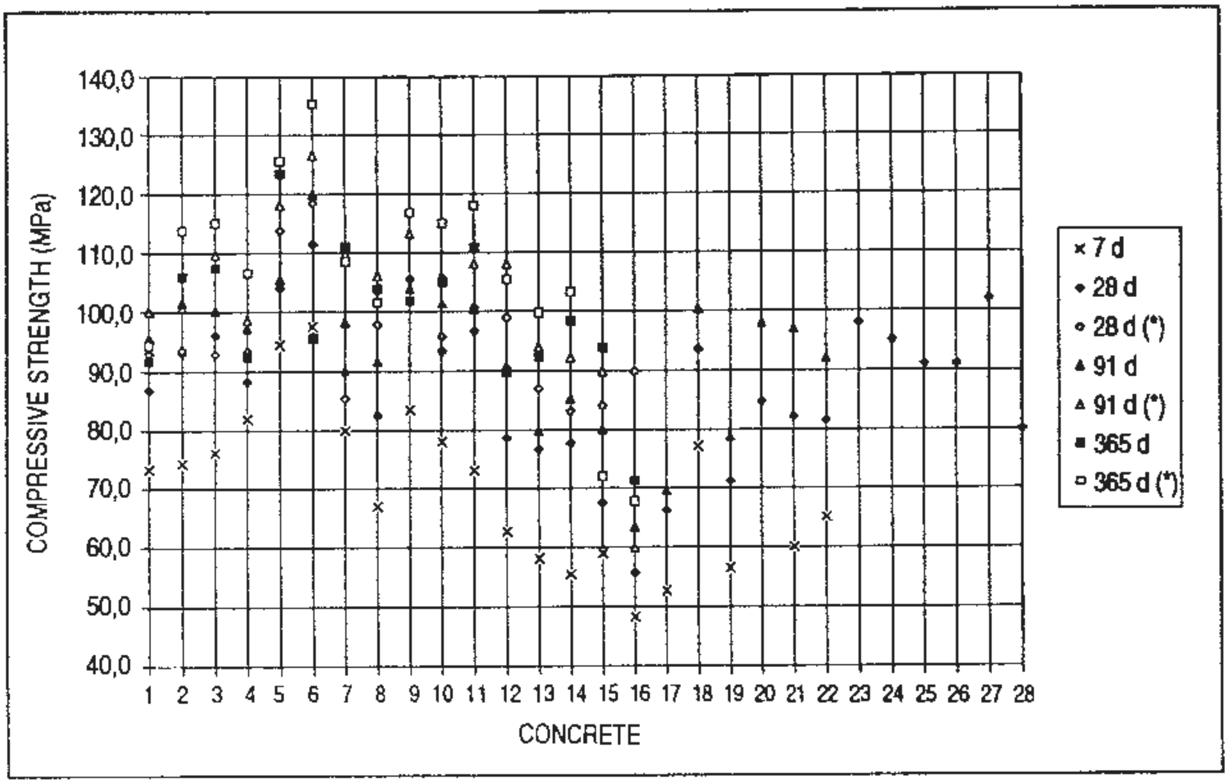

Fig. 1. Compressive strength results.

Flexural strength results are presented in Fig. 2. All these specimens cured normally at 20°C.

Table 1. Mix proportions and properties of fresh mixes.

Concrete	Cement type	Cement (kg/m3)	Silica (kg/m3)	Fly ash (kg/m3)	Blast furnace slag (kg/m3)	Aggregate (kg/m3)	Water (kg/m3)	Plasticizer (kg/m3)	Air entrainer (kg/m3)	Slump (mm)	Vebe (sVB)	Air content (%)	Water/binder ratio
1	P40/3 (*)	475.0	25.0	-	-	1761	167.0	15.0	-	155	0.5	0.8	0.35
2	P40/3 (*)	475.0	25.0	-	-	1826	142.5	15.0	-	0	8.0	2.1	0.30
3	P40/3 (*)	475.0	25.0	-	-	1868	122.2	17.5	-	5	14.0	1.4	0.26
4	P40/28SR	475.0	25.0	-	-	1827	145.2	12.5	-	170	1.7	0.8	0.31
5	P40/28SR	475.0	25.0	-	-	1883	124.0	12.5	-	115	4.0	1.2	0.26
6	P40/28SR	475.0	25.0	-	-	1915	112.2	12.5	-	50	3.9	1.6	0.24
7	P40/28SR	500.0	-	-	-	1873	130.7	12.5	-	90	4.0	1.0	0.28
8	P40/7	422.5	25.0	175.0	-	1656	148.8	12.5	-	160	0.5	1.8	0.31
9	P40/7 (*)	422.4	25.1	175.1	-	1700	132.4	12.5	-	55	4.2	2.4	0.28
10	P40/3	300.0	25.0	-	-	2036	121.8	12.1	-	170	2.1	2.6	0.40
11	P40/3	300.0	25.0	-	-	2023	126.4	12.5	-	150	2.1	2.6	0.41
12	P40/7 (*)	125.0	25.0	-	350.0	1895	109.0	14.3	-	20	5.7	1.4	0.23
13	P40/7 (*)	150.0	-	-	350.0	1912	103.6	15.0		125	8.2	2.0	0.23
14	P40/7 (*)	125.0	-	-	350.0	1896	108.5	14.3	-	70	7.2	1.2	0.23
15	P40/3	300.0	25.0	-	-	2023	126.4	12.5	0.75	20	4.9	7.0	0.41
16	P40/3	456.4	-	-	-	1743	202.3	-	0.35	55	2.0	5.1	0.44
17	P40/28SR	475.0	25.0	-	-	1772	173.3	3.3	-	85	1.4	1.5	0.35
18	P40/3	300.0	21.0	-	-	2020	120.0	9.7	-	15	5.1	1.8	0.39
19	P40/28SR	300.0	21.0	-	-	2020	120.0	9.7	-	230	3.5	1.3	0.39
20	P40/28SR	480.0	29.0	-	-	1850	137.0	12.0	-	135	3.5	1.6	0.28
21	P40/7	120.0	30.0	-	350.0	1800	114.0	20.0	-	(*)	(*)	2.2	0.25
22	P40/28SR	300.0	21.0	-	-	2020	120.0	9.7	-	150	2.9	2.0	0.39
23	P40/91	450.0	22.5	-	-	1874	122.9	11.7	-	110	4.4	1.0	0.27
24	P40/3	500.0	-	-	-	1766	155.0	15.0	-	170	< 1	2.7	0.33
25	P40/3	450.0	-	150.0	-	1610	162.0	18.0	-	180	< 1	2.7	0.29
26	P40/3	500.0	-	-	-	1783	150.0	-	-	170	3.4	1.9	0.32
27	P40/3	470.0	30.0	-	-	1791	142.4	12.5	-	95	2.8	2.8	0.30
28	P40/3	350.0	-	-	150.0	1740	167.5	10.0	-	155	< 1	0.8	0.35

(*) Mix was fluid. Result in flow table test was 655 mm.

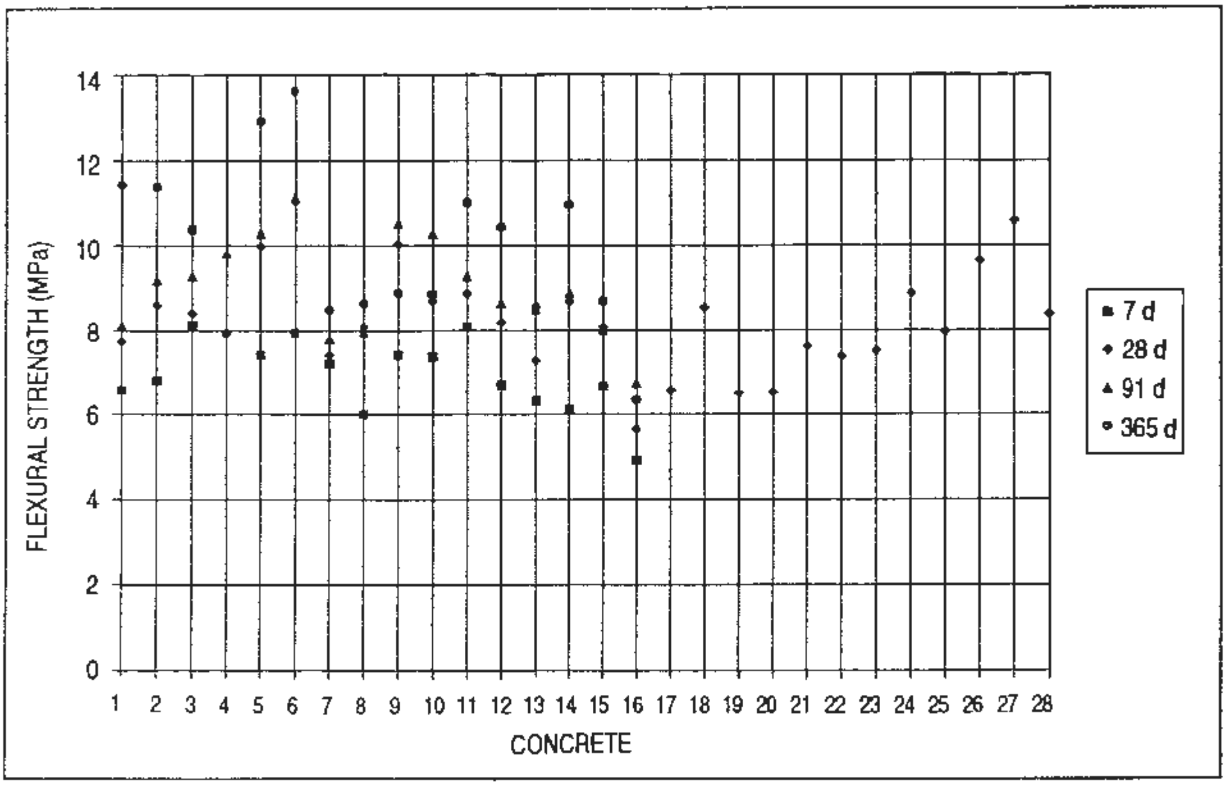

Fig. 2. Flexural strength results.

2 SALT-FROST TESTS

Salt-frost tests were performed according to Finnish standard SFS 5449. In this method the specimens (100 mm cubes) are frozen in saturated NaCl solution at -15°C, and thawed in water at +20°C. A cycle consisted of 8 hours freezing and 16 hours thawing period. 300 cycles were included in the test unless the specimens were destroyed earlier. Three samples of each concrete were tested. The percentage volume change of the samples was observed. The test results are shown in Table 2.

Table 2. Volume changes in salt-frost tests.

Concrete	**Volume change (%)**							
	10 cycles.	**25 cycles**	**50 cycles**	**100 cycles**	**150 cycles**	**200 cycles**	**250 cycles**	**300 cycles**
1	0.1	0.1	2.0	-4.2	-77.7	-	-	-
2	0.0	0.0	0.0	-0.1	-0.2	-0.3	-0.3	-0.2
3	0.0	-0.1	-0.4	-0.6	-0.7	-0.7	-0.6	-0.6
4	-0.1	-0.2	-0.5	-0.8	-1.7	-2.8	-3.3	-3.9
5	0.0	0.0	0.2	-0.2	-0.5	-0.9	-1.1	-1.2
6	0.0	0.0	0.0	0.0	-0.2	-0.5	-0.6	-0.8
7	0.0	-0.6	-1.3	-4.4	-6.7	-9.5	-12.8	-16.6
8	-0.1	-0.3	-0.5	-1.0	-1.3	-2.0	-2.2	-3.1
9	-0.2	-0.4	-0.3	-0.4	-0.8	-1.1	-1.5	-1.6
10	0.1	-0.4	-0.4	-0.7	-1.1	-1.9	-3.0	-4.1
11	-0.2	-0.4	-0.3	-0.4	-0.8	-1.5	-1.8	-3.1
12	0.0	0.0	0.0	-0.2	-0.7	-0.7	-1.0	-0.9
13	0.0	0.0	0.0	0.0	0.3	-0.2	0.0	-0.1
14	0.0	0.0	-0.1	-0.5	-0.8	-1.1	-1.2	-1.4
15	0.0	0.0	-1.2	-2.9	-4.6	-7.3	-8.8	-11.3
16	0.0	-1.5	-3.8	-9.6	-16.9	-22.7	-27.8	-31.4
17	0.0	-0.1	-0.1	-2.0	-11.7	-43.5	-85.3	-96.8
18	0.0	-0.4	-0.6	-0.5	-0.8	-0.8	-1.7	-3.0
19	0.0	-0.3	-0.5	-0.2	-1.0	-1.5	-3.9	-7.1
20	0.2	0.2	-0.3	0.6	0.7	0.6	0.9	0.6
21	0.1	-0.7	-1.5	-2.0	-1.8	-2.1	-2.2	-2.3
22	-0.1	0.2	0.6	1.0	1.5	-11.2	-	-
23	0.0	0.2	0.2	0.1	-0.1	-0.4	-0.7	-0.9
24	0.0	-0.2	-0.4	-1.9	-4.6	-8.8	-	-
25	-0.4	-1.3	-2.4	-3.7	-6.0	-8.7	-	-
26	0.0	0.1	0.2	0.0	-0.3	-0.7	-1.5	-2.1
27	0.0	0.0	0.0	0.0	0.0	-0.1	-0.3	-0.3
28	0.1	-0.6	-3.3	-8.4	-12.5	-20.0	-	-

3 RESULTS OF FREEZE-THAW TESTS

The freeze-thaw tests were made according to Finnish standard SFS 5447, which is very similar to ASTM C666 method B. In these tests the samples (three 100 x 100 x 500 mm beams from each mix), were frozen in air at -20°C and thawed in water at +20°C. Five cycles was fulfilled per day. Another series of beam specimens were stored in water for reference testing. The ultrasonic pulse velocity and mass changes were measured frequently during the test. The results are shown in Table 3.

Table 3. Ultrasonic pulse velocity and mass change results from the freeze-thaw tests.

Con-crete	**Ratio of squares of ultrasonic velocities in test and comparison beams $(v/v_v)^2$**						**Relative mass changes (%)**					
	100 cycles	**200 cycles**	**500 cycles**	**1000 cycles**	**1500 cycles**	**2000 cycles**	**100 cycles**	**200 cycles**	**500 cycles**	**1000 cycles**	**1500 cycles**	**2000 cycles**
1	0.62	0.29	0.35	0.30	(*)	(*)	0.317	0.697	1.255	1.537	(*)	(*)
2	0.95	0.94	0.93	0.93	0.94	0.97	-0.008	-0.030	-0.122	-0.100	-0.077	0.028
3	0.91	0.93	0.96	0.90	0.93	0.92	-0.037	0.069	-0.304	-0.312	-0.829	-0.869
4	0.91	0.96	0.84	0.66	0.75	0.58	0.021	0.063	0.037	0.352	0.440	0.627
5	0.95	0.98	0.95	0.93	0.70	0.85	0.118	0.259	0.199	0.186	0.828	0.821
6	0.89	0.89	0.92	0.88	0.94	0.50	-0.052	0.046	0.167	0.149	-0.008	0.651
7	0.90	0.95	0.98	0.96	0.91	0.95	0.037	0.031	0.097	-0.010	-0.043	-0.039
8	0.97	0.96	0.95	0.97	0.90	0.84	-0.011	-0.125	-0.087	-0.153	-0.188	0.358
9	0.97	0.96	0.96	0.97	0.99	0.99	-0.097	-0.063	-0.188	-0.160	-0.195	-0.233
10	0.97	0.99	0.97	0.68	0.50	0.22	-0.058	-0.063	-0.116	0.573	1.112	1.410
11	1.00	0.97	0.96	0.88	0.60	0.63	0.051	0.045	-0.027	0.287	0.338	0.207
12	0.98	0.97	1.00	0.97	0.85	0.90	-0.002	0.008	-0.061	-0.074	-0.211	-0.283
13	0.97	0.95	0.94	0.92	0.90	0.83	-0.018	-0.045	-0.123	-0.137	-0.162	-0.292
14	0.93	0.88	0.95	0.94	0.96	0.85	-0.071	-0.074	-0.126	-0.234	-0.295	-0.422
15	0.98	0.98	0.96	0.93	0.88	0.91	-0.152	-0.118	-0.140	-0.154	-0.249	-0.236
16	0.94	0.95	1.00	0.98	0.99	0.87	-0.154	-0.323	-0.188	-0.219	-0.042	0.054
17	0.30	0.25	0.07	-	-	-	0.470	0.706	1.106	-	-	-
18	0.88	0.92	0.54	-	-	-	0.045	0.206	0.834	-	-	-
19	0.91	0.68	0.33	-	-	-	0.000	0.057	0.104	-	-	-
20	0.97	0.85	0.00	-	-	-	-0.047	0.107	-	-	-	-
21	0.94	0.94	0.97	-	-	-	-0.053	-0.016	-0.032	-0.109	-	-
22	0.49	0.11	0.00	(**)	(**)	(**)	0.187	0.238	(**)	(**)	(**)	(**)
23	0.54	0.57	0.69	-	-	-	0.568	0.962	0.977	-	-	-
24	0.94	0.94	0.89	-	-	-	-0.049	0.381	0.065	-	-	-
25	0.93	0.91	0.87	-	-	-	0.163	0.000	0.123	-	-	-
26	0.98	0.91	0.91	-	-	-	-0.079	0.071	-0.055	-	-	-
27	0.97	0.96	0.91	-	-	-	0.000	0.262	0.167	-	-	-
28	0.80	0.82	0.83	-	-	-	0.016	0.041	0.212	-	-	-

(*) Two of the test beams were destroyed at 250 cycles. The rest of the results are measures from one beam.

(**) One test beam was removed after 150 cycles due to deterioration. The test continued with two specimens.

When the test beams of concretes 1 - 16 had been subjected to 1 000 freeze-thaw cycles, cubes were sawn for compressive strength testing. Similar compressive test specimens were prepared from concretes 17 - 19 after 500 cycles. The results, together with reference strength values for water cured beams of the same age, are shown in Fig. 3.

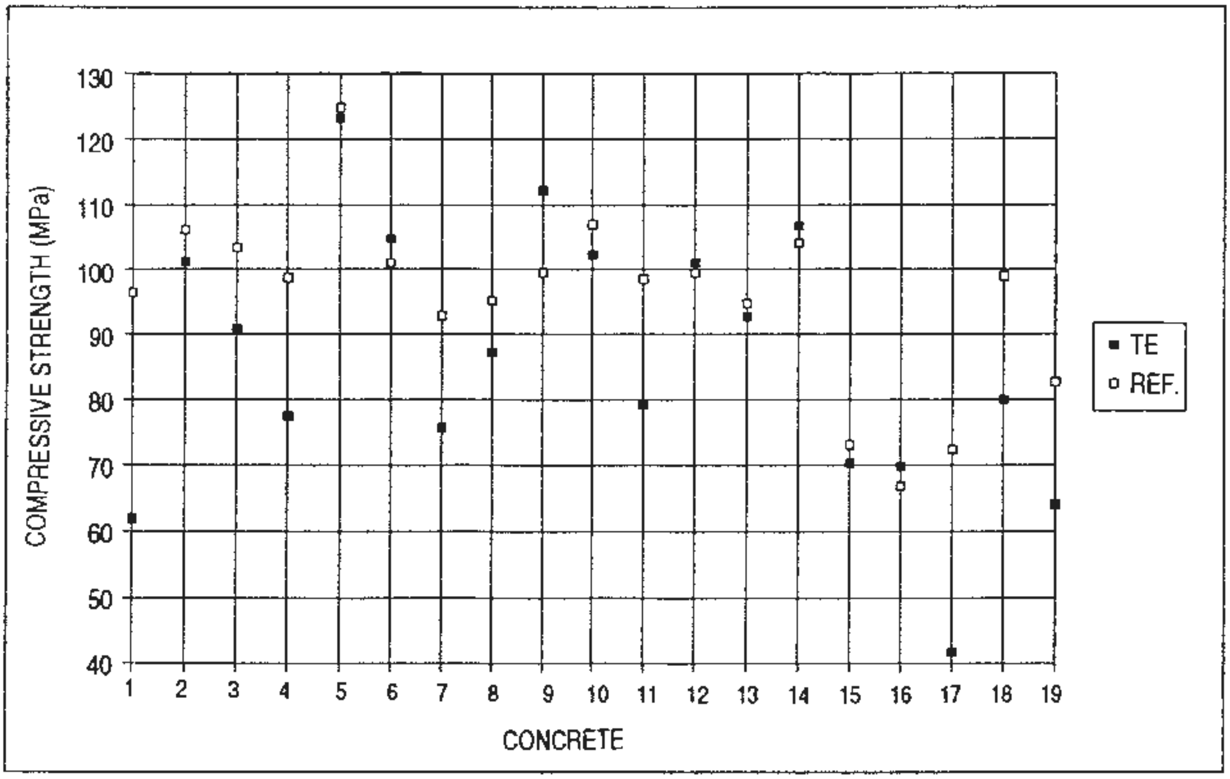

Fig. 3. Compressive strengths of concretes after 1 000 cycles (concretes 16 - 19 500 cycles) with reference compressive strengths.

Thin sections, two from each mix, were prepared from concretes 1 - 19 for microscopy studies. In most cases the thin sections were made after 1 000 cycles (exceptions were concretes 1, 250 cycles, and 17 - 19, 500 cycles). Cracking indices were determined from the thin sections. Cracking indices describe the extent and continuity of cracks and flaws in the concrete. Index 0 means that there are practically no cracks in the concrete and that they are exceptionally small. Index 3 means that the concrete is totally cracked and that the cracks are long and interconnected. The results are shown in Table 4.

Table 4. Cracking indexes of test beams and reference beams.

Concrete	Cracking index	
	Test	Reference
1	3.0	2.5
2	1.0	1.5
3	1.5	2.0
4	1.5	1.0
5	2.0	0.0
6	3.0	0.5
7	1.5	1.0
8	1.5	0.0
9	0.5	0.5
10	1.0	0.5
11	3.0	0.5
12	2.0	1.0
13	1.0	1.0
14	0.0	0.0
15	0.0	0.0
16	2.5	2.5
17	3.0	1.5
18	3.0	1.0
19	3.0	0.5

In order to clarify the effect of capillary properties on the frost resistance, capillary immersion tests were performed with samples cut from the reference concrete beams. The samples, two of each mix, were taken from the ends of the beams and 10 cm from the beam ends. The total porosity, protective pore ratio, capillary pore ratio, gel pore ratio, water penetration resistance and capillary factor were measured in the test. The results are shown in Table 5.

Table 5. Results from capillary immersion tests.

	SAMPLES FROM BEAM ENDS						SAMPLES 10 CM FROM BEAM ENDS					
Con-crete	total porosity (l/ m^3)	protective pore ratio.	capillary pore ratio	gel pore ratio	water penetration resistance (s / mm^2)	capillary factor (kg / m^2 √s)	total porosity (l/ m^3)	protective pore ratio	capillary pore ratio	gel pore ratio	water penetration resistance (s / mm^2)	capillary factor (kg / m^2 √s)
1	132.6	0.336	0.276	0.388	22.6	0.0077	126.7	0.249	0.349	0.402	21.5	0.0095
2	116.0	0.402	0.157	0.441	15.4	0.0046	123.3	0.326	0.252	0.422	26.4	0.0061
3	96.9	0.345	0.163	0.492	15.3	0.0040	101.2	0.287	0.242	0.471	22.6	0.0052
4	118.1	0.376	0.240	0.384	21.5	0.0061	114.2	0.232	0.391	0.377	35.6	0.0075
5	95.4	0.370	0.188	0.442	18.0	0.0042	105.4	0.340	0.239	0.421	20.1	0.0056
6	88.0	0.406	0.159	0.435	16.3	0.0035	88.7	0.321	0.228	0.451	29.4	0.0037
7	93.0	0.432	0.182	0.386	23.6	0.0035	97.1	0.273	0.385	0.342	26.6	0.0072
8	117.2	0.358	0.107	0.535	29.8	0.0023	120.2	0.279	0.189	0.532	20.4	0.0050
9	93.7	0.302	0.113	0.585	20.7	0.0023	102.4	0.203	0.209	0.588	27.4	0.0041
10	88.0	0.411	0.076	0.513	18.8	0.0015	102.3	0.290	0.230	0.481	39.8	0.0037
11	94.2	0.439	0.091	0.470	19.5	0.0019	104.2	0.172	0.214	0.614	18.7	0.0052
12	95.8	0.436	0.188	0.375	31.2	0.0032	101.1	0.295	0.222	0.484	25.2	0.0045
13	93.0	0.503	0.127	0.370	19.0	0.0027	92.9	0.316	0.203	0.481	20.9	0.0041
14	93.6	0.430	0.178	0.392	31.5	0.0030	105.0	0.284	0.237	0.478	28.5	0.0047
15	120.9	0.455	0.120	0.425	33.4	0.0025	114.3	0.239	0.165	0.596	17.2	0.0045
16	165.7	0.520	0.145	0.335	28.9	0.0045	182.0	0.268	0.336	0.396	30.8	0.0110
17	129.3	0.429	0.228	0.343	22.8	0.0062	92.5	0.230	0.513	0.257	25.1	0.0095
18	99.9	0.436	0.106	0.458	15.6	0.0027	99.4	0.198	0.184	0.618	16.5	0.0045
19	98.8	0.507	0.148	0.345	33.3	0.0025	104.9	0.261	0.273	0.466	23.1	0.0060

4 FACTORS AFFECTING SALT-FROST RESISTANCE

It is difficult to see any clear dependence between any of the properties of the materials in the mixes and salt-frost resistance. The most evident conclusion is that the two air-entrained mixes showed less salt-frost resistance than expected. There seems to be no clear reason for the poor resistance of mix 17 with sulphate resistant cement and low amount of superplasticiser.

Because there were no apparent reasons for the differences in the results, the results from salt frost testing of the concretes were treated statistically. The aim of the calculations was to find a statistical and simple basis for describing the salt-frost resistance of non-airentrained high strength concrete. A confidence limit of 95% was used as a basis of model acceptance. Also the parameters and factors in the models are statistically significant. The parameters in the analysis included the amounts of concrete constituents, water/cement ratio, workability, air content, compressive and flexural strength and the results of capillary immersion tests.

There was no strong correlation between any of these parameters. The strongest was the correlation between 300 cycles salt frost resistance and the ratio of capillary porosity to total porosity and the capillary factor measured from samples 100 mm from beam ends. Linear regression analysis did also not give satisfactory results.

Salt frost resistance was best explained by the capillary factor as:

$$|y| = (47\ 10^6\ x^3 - 0.51\ 10^6\ x^2 + 1600\ x)^2 \qquad (1)$$

where x is the capillary factor in $(kg\ /\ m^2\ \sqrt{s})$ and y the residual percentage volume after 300 cycles. The coefficient of determination for this formula is 0.96. A simple formula a little bit on the safe side is the following:

$$|y| = (0.152\ 10^6\ x^2 - 510\ x)^2 \qquad (2)$$

The coefficient of determination is about 0.91.

Because the capillary factor can only be measured from hardened concrete, a model based on mix design parameters is more practical. The capillary factor correlated strongly with the water/binder ratio and water content in the test concretes without air entrainment and the same amount of cement, 450 - 480 kg/m^3. These were concretes 1 - 6, 17, 20, 23 and 27. The water/binder ratio (w) estimates the salt-frost resistance in the following way:

$$|y| = (1685\ w^2 - 923\ w + 126)^2 \qquad (3)$$

The coefficient of determination for this model is 0.97.

5 FACTORS AFFECTING FROST RESISTANCE

Deterioration in freezing and thawing is difficult to follow numerically because there is no single test for deterioration. The ultrasonic pulse velocity may change for various reasons, e.g. when cracking takes place and also when the cracks are filled during the test. Mass changes do not describe deterioration as well as in the frost tests with salt. In this study, the effects of the frost test are discussed on the basis of strength changes after 1 000 cycles compared with reference results from water cured specimens.

A survey of the results indicates that water-binder ratio is an important factor in estimating the frost resistance. The less resistant concretes tend have a relatively high water-binder ratio.

The effect of binder is not distinct in the results. Both fly ash and blast furnace slag concretes gave good results. The effect of aging may be of importance when slag or a large amount of silica are used. These effects have been studied elsewhere /2/. Air entrainment seems to be clearly more efficient than in the case of salt-frost resistance.

The capillary factor seems to explain frost resistance quite well also here. However, air-entrained concretes and concretes with fine quartz filler do not fit in a model based on the capillary factor.

Statistical curve fitting gives the following equation:

$$j = -45\ 10^6\ x^2 - 430\ x \tag{4}$$

where j is the ratio of compressive strength of the test specimen after 1000 cycles to the compressive strengths of reference specimens, and x the capillary factor measured from a sample 10 cm from beam end. The coefficient of determination for this model is as good as 0.994. As a simple model based on a mix design the parameter could be calculated from the following formula:

$$j = -40.0\ w^2 + 14.3\ w \tag{5}$$

where w is the water/binder ratio. This formula is applicable to concrete without by-products. The results do not yield reliable models for concretes with binders other than cement. As stated before, the capillary factor indicates generally quite well the salt-frost and frost resistance of high strength concrete. The capillary index can, however, be estimated on the basis of the water/binder ratio only in relatively homogeneous concrete groups.

Generally, the estimation of freezing and thawing resistance of non-airentrained concretes with water/binder ratio between 0.3 and 0.4 has proven to be difficult due to large variations of durability with relatively small changes in mix design. Uncertainty of air entrainment and its practical problems are significant in the strength area of 80 MPa and above. Below water/binder ratio 0.3 the frost resistance of concretes with conventional constituents is generally good.

6 CONCLUSIONS

The results show that air entrainment of high strength concrete is not necessary if the capillary factor is beneficial. Statistical models for durability can be based on the capillary factor. The water/binder ratio or water content of the mix can be used for calculating durability with concretes having similar binders and roughly the same binder contents.

7 LITERATURE

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